A Study of the Characteristics and Assimilation of Retrieved MODIS Total Precipitable Water Data in Severe Weather Simulations

Shu-Hua Chen[12@], Zhan Zhao[1], Jennifer S. Haase[3], Aidong Chen[1], Francois Vandenberghe[4]

[1]Department of Land, Air, and Water Resources, University of California, Davis, CA

[2]Department of Atmospheric Sciences, National Central University, Chung-Li, Taiwan

[3]Department of Earth and Atmospheric Sciences, Purdue University, W. Lafayette, IN

[4]National Center for Atmospheric Research, Boulder, CO

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[@]Corresponding author's address: Shu-Hua Chen, Department of Land, Air, and Water Resources, University of California, Davis, California 95616-8627; E-mail: shachen@ucdavis.edu.

Abstract

The Moderate Resolution Imaging Spectrometer (MODIS) provides total precipitable water (TPW) data over land and ocean using near-infrared reflectance at a resolution of 1km, which gives it the potential to significantly improve weather forecasts. This study determined the accuracy and biases associated with MODIS TPW data and investigated the impact of its assimilation into the Weather Research and Forecast Model (WRF). A comparison between MODIS TPW and Global Positioning System (GPS) TPW over the United States showed that the root mean square (RMS) differences between these two data sets was about 5.2 and 3.3 mm for infrared (IR) and near-infrared (nIR) TPW, respectively. The comparison also showed that there were biases for both retrieved IR and nIR TPW data. The MODIS IR TPW data were overestimated in a dry atmosphere but underestimated in a moist atmosphere. In contrast, the nIR values were slightly underestimated in a dry atmosphere but overestimated in a moist atmosphere. Linear relations were developed to correct the biases associated with these data. The bias correction of MODIS nIR TPW reduced the RMS difference to 2 mm. Comparisons with radiosondes in the US and Australia also showed a similar trend in the differences with MODIS TPW, but with a larger offset, which may be associated with the previously reported dry bias in radiosonde measurements.

Two severe weather simulations, a severe thunderstorm system (2004) over land and Hurricane Isidore (2002) over the ocean, were used to assess the impact of assimilating MODIS nIR TPW data, as well as conventional observations and Special Sensor Microwave Imager (SSM/I) retrievals. One set of experiments was conducted for the thunderstorm case and two sets for the Isidore case. The use of conventional observations alone had almost no impact on the thunderstorm system over land, but conventional observations were able to improve the Isidore simulations, in particular in the direction of storm motion. The assimilation of original or bias-corrected nIR MODIS TPW showed a slightly positive impact on simulated rainfall over Oklahoma, the region of interest, for the thunderstorm case. For Isidore, the simulated storm intensities were too weak or too strong depending on the start time of integration of the simulation and the error in the reproduced storm track. MODIS nIR TPW was able to enhance

Isidore's intensity when the storm track was reasonably simulated. However, compared with original data, the bias correction of MODIS nIR TPW did not show any improvement and even slightly degraded one of the Isidore simulations. The assimilation of SSM/I data had a positive impact on both severe weather simulations and the impact was comparable to or slightly better than that of MODIS data. In addition, the influence of SSM/I data on the Isidore simulation occurred earlier than that of MODIS data due to clouds over the storm region that reduced the quantity of MODIS data available.

1. **Introduction**

In the past two decades, remote sensing instruments (e.g., radar and satellites) have added a tremendous amount of data to existing observation networks. This is leading to important advances in our knowledge of the dynamics and physics of weather phenomena (Huang et al. 2006, Wang and Michelangeli 2006), improvements in weather simulations and forecasts (i.e. Gerard and Saunders 1999; Hou et al. 2000; Pu and Braun 2001; Leidner et al. 2003; Chen et al. 2004; Isaksen and Janssen 2004; Huang et al. 2005; Zhang et al. 2007), and support for the study of climate change (Lau and Chan 1983, Andrew 1987, Steffen et al. 1993, Chelton and Wentz 2005). Improvements in the ability to observe the distribution and propagation of atmospheric moisture play a critical role in these advances. Many instruments onboard satellites have been monitoring atmospheric moisture information, such as the Special Sensor Microwave/Imager (SSM/I), the Geostationary Operational Environmental Satellites (GOES), the Microwave Sounding Unit (MSU), the Humidity Sounder for Brazil (HSB), the Atmospheric Infrared Sounder (AIRS), and the Moderate Resolution Imaging Spectrometer (MODIS). Instruments that detect InfraRed (IR) frequencies (e.g., GOES, AIRS) can measure moisture over land and ocean in cloud free regions. Those instruments which use microwave frequencies (e.g., SSM/I, HSB, and MSU) can measure moisture under both clear and cloudy conditions, but only over the ocean. These microwave data, unfortunately, can be contaminated by heavy precipitation. MODIS is the first space instrument that uses nIR bands together with the traditional IR bands to obtain total precipitable water (TPW) information over land an ocean in cloud free regions and above cloud tops in cloudy regions. This study addresses the capabilities of the MODIS instruments in moisture measurements and demonstrates its potential for contributing to improvements in weather simulations, in particular for data retrieved from nIR channels.

Both the Terra satellite (launched February 2000) and the Aqua satellite (launched May 2002) are equipped with the MODIS scanning spectroradiometer. MODIS detects electromagnetic radiation in thirty-six spectral bands between 0.4 and 14.4 μm with spatial resolutions of 250 m (2 bands), 500 m (5 bands), and 1000 m (29 bands) (King et al. 1992). The swath width of the MODIS data is 2300 km for Terra and 2330 km for Aqua, and the satellites are in polar sun-synchronous orbit at an altitude of 705 km. The retrieved nIR MODIS TPW, which is available during daytime only, is derived from two water vapor absorption bands centered near 0.905 and 0.94 μm and three water vapor window bands centered near 0.865, 0.936, and 1.24 μm. The ratio of reflected solar radiances from an absorption channel and a window channel is used to derive atmospheric water vapor transmittances; the column total precipitable water (TPW) is then obtained from the transmittances using a lookup table that was pre-calculated with a line-by-line atmospheric transmittance code (Kaufman and Gao 1992; King et al. 2003). The quality of MODIS nIR TPW relies on observed water vapor attenuation of nIR solar radiation which is reflected by surfaces and clouds. Therefore, the accuracy of retrieved MODIS nIR TPW data strongly depends on the estimation of surface reflection. A larger error can be introduced over regions where surface reflection is small in nIR channels, such as the ocean, except for sun glint areas where the surface reflectance is relatively high (Kleidman et al. 2000).

The retrieved MODIS IR TPW is derived from bands 24 to 36 (between 4.47 to 14.24 μm), excluding band 26, and is available during both day and night. A statistical regression algorithm, with an option of a subsequent non-linear physical retrieval, is used to retrieve atmospheric temperature, moisture, ozone profiles, and skin temperature (Seemann et al. 2003). Through the use of a linearized radiative transfer model and the inversion of radiance measurements, the regression coefficients were derived from a set of global radiosonde soundings and the radiances that were computed from those soundings. The linearized radiative transfer model has 101 pressure levels from 0.05 to 1100 hPa. Therefore, retrieved vertical moisture profiles have the same number of levels, which are then used to integrate the MODIS IR TPW.

Several studies of MODIS TPW data have contributed to satellite commissioning and calibration. Kaufman and Gao (1992) showed that the error of the airborne version of MODIS nIR TPW was as low as 7% after the incorporation of additional MODIS channels that reduced the effects of uncertainties in surface reflectance, subpixel clouds, haze and temperature profile on the derived water vapor. Based on theoretical calculations and lookup tables, Gao and Kaufman (2003) estimated that the error of MODIS nIR TPW was about 5% to 10%. Kleidman et al. (2000) compared MODIS nIR TPW from the Airborne Simulator with that from the Differential Infrared Absorption Lidar system onboard the NASA ER-2 research aircraft, over ocean sun glint regions. They found that the error of estimated MODIS nIR TPW was about 5 mm and the TPW amounts were underestimated when the column water vapor content was relatively low. Seemann et al. (2003) compared the MODIS IR TPW data from Aqua and Terra with that from SSM/I, GOES, radiosondes, and the ground-based microwave radiometer (MWR) at the Atmospheric Radiation Measurement (ARM) Program Cloud and Radiation Test Bed (CART) in Oklahoma. Their results from the comparison with MWR data showed that the root mean square error of the regression-based MODIS IR TPW was 4.1 mm. For a dry atmosphere, retrieved MODIS IR TPW, using either physical or regression-based algorithms, was overestimated by 3.7 mm on average, and for a moist atmosphere it was underestimated by 1.2 mm.

With such high spatial resolution data, it was hoped that MODIS TPW would be able to improve weather forecasts. However, relatively few studies beyond MODIS TPW data comparison and calibration have been carried out so far. Chang et al. (2007) assimilated retrieved temperature and dew points from MODIS IR channels for Hurricane Lili (2002) simulations, and the simulated storm intensity was slightly improved. Though assimilation of satellite data is challenging, many studies with other instruments have shown improvements of weather simulations/forecasts (Gerard and Saunders 1999; Deblonde 1999; Xiao et al. 2000; Chen et al. 2004; Lagouvardos and Kotroni 2005; Chang et al. 2007; Chen 2007), while a smaller number of cases showed a negative impact or almost no improvement (Zou et al. 2001; Chen 2007). The assimilation of MODIS TPW is expected to be equally or more challenging due to the potential for data biases and the difficulty of cloud mask determination.

This work deals with the development and testing of the assimilation of MODIS nIR TPW and some of the challenges associated with this particular dataset. The error characteristics of MODIS nIR and IR TPW are analyzed by comparing them with independent observations from the ground-based Global Positioning System (GPS) in the US and from computed TPW from radiosonde soundings in the US and Australia in section 2. The Weather Research and Forecasting (WRF) model variational data assimilation system (WRF-Var, Skamarock et al. 2005) used for the testing, its configuration, and the experimental design are introduced in section 3. Some preliminary results assessing the impact of assimilating MODIS nIR TPW are demonstrated using two severe weather cases in section 4 and brief concluding remarks are given at the end.

2. Observations and Data Comparison

2.1 Data

An example of the MODIS level 2 nIR and IR TPW data (MOD05 products) (Gao and Kaufman 2003; Seemann et al. 2003) are shown in Figure 1 from the Aqua satellite granule between 1840 and 1845 UTC 19 September 2002 at the time when Hurricane Isidore moved to southwest of Cuba (white cross in Fig. 1). MODIS IR data were void in cloudy regions, such as directly over Hurricane Isidore and its vicinity, while MODIS nIR data were available in those regions but the values were integrated only above the cloud top, and thus were significantly lower compared to the integration of the whole column. Therefore, the detection of cloudy pixels, as well as data quality control, can be crucial when assimilating MODIS nIR TPW data.

The MODIS TPW data have a spatial resolution of 1 km and 5 km for nIR and IR TPW, respectively. To make both datasets comparable, MODIS nIR data were smoothed to a 5-km resolution by averaging data from cloud free pixels in 5 x 5 matrices, with a required minimum of 10 clear-sky pixels identified using the cloudiness flag provided in the dataset. To understand the characteristics of the retrieved MODIS TPW and to better use those data in assimilation, the IR and nIR data were compared with two independent observations over different regions: retrieved TPW from ground-based GPS receivers and computed TPW from radiosondes. For GPS, data from 16 May to 9 June 2004 from 101 sites over the continental US were retrieved from the National Oceanic and Atmospheric Administration (NOAA) Forecast System Laboratory (Gutman et al., 2004). For the radiosonde comparisons, soundings over the US around 0600 and 1800 UTC from 2002 to 2005 were used. In addition, radiosondes from Australian stations (Fig. 2) were chosen since the satellites pass the eastern region of the country at the time when radiosondes were launched (around 0000 and 1200 UTC). Two months, January (summer in southern hemisphere) and July (winter) 2003, were selected for the comparison. Because of the continuous nature of GPS TPW data, the time difference between GPS and MODIS data was very small. The maximum distance separation allowed for data comparison between MODIS pixels and GPS TPW site locations was 10 km. For radiosondes, the maximum time and space differences between the launch site and the MODIS data pixels were 1.5 h and 30 km, respectively.

2.2 Data comparison

About 2000 MODIS nIR and 6000 IR data points were compared with GPS TWP over the continental US. In all the nIR comparisons in this study, we excluded any points whose values were significantly underestimated (ie by more than 5mm), as probably being due to the existence of clouds that were not accurately characterized by the cloud mask algorithm. (i.e., those in the dashed box in Fig. 3a), For nIR data, the retrieved TPW matched GPS TPW very well, particularly when MODIS values were small (i.e., a drier atmosphere) (Fig. 3). The MODIS nIR TPW was on average 1.8 mm moister than GPS TPW, as shown in Table 1, and the root mean square (RMS) was about 3.3 mm . The variation of the differences became larger as the column moisture content increased (Fig. 3a). MODIS IR TPW also matched GPS TPW quite well (Fig. 3b). The mean of the differences was about 0 mm and the RMS was 5.2 mm (Table 1). The variation was greater than that from nIR retrievals,), implying that the uncertainty associated with MODIS IR TPW is greater that that with MODIS nIR TPW, and the range was almost independent of the column moisture amount.

Figure 4 shows the differences between MODIS TPW and GPS/radiosonde TPW and their linear regression relationships. Compared with GPS TPW (light-grey crosses and the light-grey solid line in Fig. 4a), the MODIS nIR values were slightly underestimated in a dry atmosphere and overestimated in a moist atmosphere. The overestimation increased as the column water vapor content increased. A previous study comparing MODIS data to a small number of data from only two sites (Li et al. 2003) also found an overestimation for a moist atmosphere. That study showed MODIS TPW=1.09 x GPS TPW - 0.3 mm for one site in England and MODIS TPW=1.14 x GPS TPW - 0.1 mm for the ARM site in the US Great Plains, whereas our study shows on average MODIS TPW=1.14 x GPS TPW - 1.46 mm for 101 sites. The comparison here from a larger number of sites includes a much larger range of TPW values, up to 50 mm, and is more robust for bias correction over a larger geographic region, especially at lower latitudes. Previous comparisons over sun glint regions over ocean also found an underestimation of MODIS nIR TPW in a dry atmosphere (Kleidman et al., 2000). The larger error in their study (about 5 mm) might be due to a larger uncertainty of the estimated surface reflectance, an important factor in the quality of retrieved nIR TPW over the ocean.

Compared with GPS results, a similar regression trend (or slope) was shown in the difference between the MODIS nIR TPW and computed radiosonde TPW from the US (116 data points; black filled triangles and the black solid line in Fig. 4a). However, the regression line has a higher positive bias. This was also shown in the comparison with radiosondes from Australia (about 550 data points; black opene circle and the grey dashed line in Fig. 4a). This is consistent with the reported dry bias for moisture measurements from the RS80 and RS90 radiosondes (Wang et al. 2002; Miloshevich et al. 2006) that have been widely used in Australia and the US, respectively. The mean differences in the radiosonde comparison, 3.5 mm and 2.8 mm, respectively, were larger than that from GPS TPW (Table 1). A comprehensive study comparing GPS and radiosonde data in Europe (Haase et al. 2003) showed that biases exist between the GPS and radiosonde data, with GPS data being moister overall. This bias, however, was shown to have an annual signal and was strongly associated with daytime radiosonde measurements, possibly indicating solar heating biases in the radiosondes. This is consistent with our results, which are also from daytime only.

For the MODIS IR data, comparison with GPS TPW (grey crosses and the grey line in Fig. 4b) indicated that the MODIS values were very likely overestimated for a dry atmosphere and underestimated for a moist atmosphere. The trend of the bias is consistent with that reported in Seemann et al. (2003). The comparison of MODIS IR TPW with radiosonde TPW over the US and Australia also shows a similar result. The average differences of MODIS IR TPW from GPS TPW and from radiosondes over the US were about 0 and 2.1 mm, respectively, and for radiosondes over Australia were 1.5 mm (Table 1). This again shows that compared with GPS, lower values were obtained from radiosonde instruments, in particular for a moist atmosphere. In this study, only GPS TPW data were used to estimate the bias of MODIS TPW because of the dry bias potentially associated with radiosonde data.

The MODIS data near the Willis Island radiosonde site (see Fig. 2a for the location) were mostly underestimated for nIR data and mostly overestimated for IR data. This is the opposite trend shown at the other radiosonde sites. The observed MODIS TPW over this island might represent a marine atmosphere rather than a continental atmosphere. This systematic underestimation associated with the MODIS nIR TPW data on Willis Island could be due to lower reflectivity over the surrounding ocean region or due to the possibility that there was cloud around the island most of time. This implies that the bias of MODIS TPW data, either IR or nIR, over the ocean can be very different from that over the land. Since the GPS data that were used for bias estimation in this study were from the US continent, the bias correction in the data assimilation study in Section 3 will be applied to data over land only.

2.3 Bias correction for MODIS nIR TPW

Based on the data comparisons, the uncertainty of the MODIS nIR TPW is smaller than the IR TPW. Therefore, in this study only MODIS nIR data were corrected and evaluated using data assimilation and model simulations. The bias-corrected MODIS nIR TPW, TPW_n, was calculated as follows:

$$TPW_n = (1-0.17)\times TPW_o + 0.24, \qquad (1)$$

where TPW_o denotes the original MODIS nIR TPW value. This formula was used to correct MODIS nIR data in the numerical experiments in Section 3. Note that (1) was derived from the correlation between the differences versus MODIS nIR TPW, instead of the GPS TPW, because the bias must be corrected based on the observed original MODIS TPW, not the true TPW The averaged differences of bias-corrected MODIS nIR TPW from GPS TPW over the US and radiosondes over the US and Australia were reduced to 0 mm, 2.3 mm, and 2.3 mm, respectively, and the RMS differences were improved to 2.0 mm, 3.7 mm, and 3.2 mm, respectively (Table 1).

3. Numerical Configuration and Experimental Design

The Advanced Research WRF model (ARW) version 2.0 (Skamarock et al. 2005; Michalates et al. 2001) was adopted for numerical simulations. The ARW model is a compressible, three-dimensional, non-hydrostatic model using terrain-following coordinates and its governing equations are written in flux-form. The Runge-Kutta third-order time scheme was employed and fifth- and third-order advection schemes were chosen for the horizontal and vertical directions, respectively. The WRF variational data assimilation (WRF-Var) system (Skamarock et al. 2005) was used to assimilate observations. In this study, the assimilation of MODIS TPW was developed and implemented in the WRF-Var system to assess the impact of MODIS nIR TPW on severe weather simulations. The assimilation of SSM/I data has been previously developed and tested (Chen et al. 2004) and the same methodology was applied here.

3.1 Cases

Two cases were studied: one over land and the other over ocean. The first case was a system of severe thunderstorms which occurred during early June 2004 over the central and southern US. The storm system, producing strong wind and hail, moved southward from Oklahoma towards the northern border of Texas. Between 1710 UTC 2 June 2004 and 0120 UTC 3 June 2004, sixty-one reports of hail were registered with size ranging from 0.75” to 1.75”. In Arkansas, later in the day on 2 June, hail-producing storms were spotted across the northern counties. In southwestern Arkansas, a line of strong to severe thunderstorms swept across the southern and western counties. The second case is Hurricane Isidore, which occurred in September 2002. Isidore started as a tropical wave off the coast of Africa on 9 September 2002, and became a tropical storm around 0600 UTC 18 September. The storm was classified as a hurricane at 1800 UTC 19 September. Isidore reached a maximum intensity with winds of 55 ms^{-1} at 1800 UTC 21 September and a minimum sea level pressure of 934 mb at 1200 UTC 22 September near the north coast of Yucatan. More information about Isidore can be found in the National Hurricane Center tropical cyclone report at www.nhc.noaa.gov/2002isidore.shtml.

3.2 Numerical experiment design

Three sets of numerical experiments were conducted, one for the thunderstorms over land and the other two for Isidore over the ocean. For each set, seven numerical experiments were designed, as shown in Table 2. Surface observations and radiosondes (GTS), (original) MODIS nIR TPW from Aqua and Terra, bias-corrected MODIS nIR TPW, and retrieved SSM/I sea surface wind speeds and TPW were used for assimilation. The retrieved SSM/I data were available over ocean only. For brevity, MODIS data will refer to MODIS nIR data in the remainder of the paper, unless otherwise specified. Bias correction was performed on MODIS data pixels over land only in both the thunderstorm and hurricane cases.

A two-domain nested grid with two-way interactions with resolutions of 30 and 10 km was configured for all simulations. The grid dimensions were 144 x 132 x 31 for domain 1 and 226 x 187 x 31 for domain 2 in the east-west, north-south, and vertical directions, respectively. The following parameterizations were activated for both domains: Purdue-Lin microphysics scheme (Chen and Sun 2002), which is based on Lin et al (1983) and Rutledge and Hobbs (1984) with some modifications; new Kain-Fritch cumulus parameterization (Kain 2004), which includes deep and shallow convection; Yonsei University (YSU)) boundary layer parameterization, which accounts for local and non-local mixing (Hong et al. 2006); Dudhia shortwave parameterization (Dudhia 1989); and Rapid Radiative Transfer Model (RRTM) longwave parameterization (Mlawer et al. 1997). Reanalysis data from the Global Forecast System (GFS) with a spatial resolution of 1^{o} x 1^{o} were used for boundary conditions and initial conditions. The model was integrated for 72 hours with a time step of 90 seconds for domain 1 and 30 seconds for domain 2.

For each numerical experiment, a six-hour data cycling period with the assimilation of different observations was performed for both domains before the 72-h model integration (Tables 2 and 3). The assimilation of observations was carried out at exact hours with a 1-h time window centered at the analysis time of the three-dimensional variational data assimilation, 3DVAR (i.e., analysis time $\pm$ 0.5h). Since some observations were assimilated into the GFS reanalysis, the assimilation of observations started 1 h after model integration during the 6-h data cycling period if observations were available. In this study, the conventional observations (i.e., GTS) were assimilated only at those times when MODIS data were also available. Note that all O2 experiments began with GFS reanalysis at 1200 UTC 18 September 2002 (i.e., cold start). For consistency, a six-hour data cycling period was also executed for LN, O1N, and O2N experiments prior to the 72 h integration, but no data were assimilated. Since there are no MODIS data available over the severe weather region (e.g., hurricane, convective clouds), the cold start model configuration (i.e., no clouds in the background field) will require some time for data outside this region to propagate in and potentially influence the severe weather simulation/forecast. In other words, the impact of MODIS data on severe weather simulations/forecasts might be delayed when using a cold start configuration.

3.3 Error variances, data quality control, and data reduction for data assimilations

To be conservative, the observational errors input for MODIS TPW data were similar to, but slightly larger than, those estimated from the comparison with GPS data in Section 2. For the original MODIS data an error of 4 mm was used for data over both land and ocean. After bias correction, which was applied to data over land pixels only, an error of 2.5 mm was used over land pixels and the value of 4 mm was maintained over ocean pixels. Following Chen et al. (2004), the errors for retrieved SSM/I TPW and sea surface wind speeds were 2 mm and 2.5 ms^{-1}, respectively. For conventional observations, the default errors that came with the WRF-Var package were used.

Three steps of data selection criteria were performed before MODIS TPW were assimilated. First, a 1-h time window centered at the analysis time (i.e., data assimilation time) was used to cut off data. This was applied to SSM/I data as well. Second, cloudy data were screened using the cloud flag in the MODIS dataset. As mentioned earlier, the nIR data were smoothed to a 5-km resolution from cloud free pixels in 5 x 5 matrices, and a minimum of 10 clear-sky pixels was required. Figure 6a shows an example of the coverage of a 5-min MODIS TPW granule from 1640 to 1645 UTC 1 June 2004 after the removal of cloudy data. The results corresponded well to cloudy pixels identified by visual inspection of visible channels (Fig. 6b). Data over cloudy regions, such as southern Louisiana, Mississippi, Alabama, Georgia, and central northern Gulf of Mexico in Fig. 6, were removed. The last step was the gross error check. MODIS TPW data that differed from the model's background by more than 10 mm were excluded, while for conventional data and SSM/I those with differences greater than 5 times the observational standard deviation error, a default value, were removed. Since the prescribed observational errors were different for original and bias-corrected MODIS TPW (the former 4 mm and the latter 2.5 mm), a number of 10 mm instead of 5 times the observational standard deviation error was used for the MODIS gross error check to keep the numbers of MODIS TPW data comparable in different experiments.

A simple data reduction process was performed for SSM/I and MODIS data to decrease the correlation of observations within the same grid box. For each type of satellite observations, if the data resolution was greater than the model horizontal resolution, data were reduced by simply taking the average of the valid points within each grid box. Therefore, for each satellite data, at most one observation existed inside each grid box after the data reduction.

4. Numerical Simulation Results and Discussion

4.1 Thunderstorm simulations in the central to southern US

Figure 7 shows the sea level pressure (SLP) and 100-m wind speeds and wind vectors of the thunderstorm case from the GFS reanalysis and from 30-h model simulations at 0000 UTC 3 June 2004, within the time period when high winds and heavy rainfall were observed over the Oklahoma region. In the GFS reanalysis (Fig. 7a), strong low-level north-easterly winds around central Oklahoma and southerly winds from western to central Texas with a maximum of about 10 ms^{-1} formed a convergence zone over the border of these two states. The simulated winds in central Oklahoma from LN, which did not assimilate any data, and from LG, which assimilated conventional GTS data, were too weak and the location of maximum wind speeds was shifted to the southwest. Those with the assimilation of MODIS TPW, either with (LGB) or without (LGM, LM, and LGSM) bias-correction, were stronger but the shift of the maximum wind location still existed. Through a nonlinear interaction, the assimilation of MODIS TPW could modify wind and temperature during model integration. Unfortunately, the simulated winds in southern Kansas and in the zone from northeast Mississippi to the border of Arkansas and Louisiana were too strong after assimilating MODIS data. The easterly component of simulated wind directions around central Oklahoma was too high for all experiments.

For the southerly wind from western to central Texas, simulated results from LN and LG did not pick up the right strength and direction because the low pressure system that propagated into domain 2 from the western boundary moved too slowly relative to the reanalysis. On the other hand, the simulated low pressure system from LM, LGM, and LGB propagated into domain 2 approximately at the right time as in the reanalysis and the simulated strength and directions of southerly winds were more reasonable, but slightly shifted northward. Therefore, the convergence zone over the border region between Oklahoma and Texas was better simulated in those tests with the assimilation of MODIS TPW (i.e., LM, LGM, LGB) than the tests without (i.e., LN and LG). The simulated wind over the north to north-eastern region of domain 2 was too strong (Fig. 7b) without the MODIS TPW and was slightly improved with MODIS TPW in north-eastern Kansas and northern Missouri.

Results from the (additional) assimilation of SSM/I retrievals were unexpectedly similar to those from the assimilation of MODIS TPW (i.e., LGM versus LGMS and LGM versus LGS in Fig. 7), such as east-northeasterly winds in Oklahoma, southerly wind in Texas, and the low pressure system passing through the western boundary. This implies that the information from assimilating SSM/I data, which were available over ocean only, has been propagated inland and influenced the region of interest (i.e., Oklahoma and northern Texas). Compared with GFS reanalysis and LN, the assimilation of MODIS TPW was incapable of weakening low-level winds over northern Florida. This was improved slightly with GTS (Fig. 7c) and/or SSM/I data (Fig. 7g).

Figure 8 shows the observed and simulated 12-h accumulated rainfall from 1500 UTC 2 June to 0300 UTC 3 June 2004 (21h – 33h simulation). Heavy precipitation was observed over eastern Oklahoma, the border region between Oklahoma and Texas, eastern Florida, and the area of Alabama, Georgia, and Florida near Tallahassee (Fig. 8a). The LN experiment did not reproduce rainfall over Oklahoma and eastern Florida (Fig. 8b). In addition, too much rainfall was generated in northern Louisiana. Simulated rainfall after the use of conventional GTS data (i.e., LG; Fig. 8c) was similar to that from LN but was slightly improved near Tallahassee. A false alarm was produced in southern Mississippi. Compared with LN, the assimilation of MODIS TPW in LM slightly improved the rainfall over the Oklahoma region because of an improved reproduction of the convergence zone mentioned earlier, but the amount and geographical extent were greatly underestimated; rainfall near Tallahassee (Fig. 8d) was slightly improved and that over northern Louisiana was removed. Neither LM nor LN reproduced rainfall in eastern Florida. The assimilation of GTS data plus MODIS TPW, either with or without bias correction, generated similar results to LM. However, the simulated precipitation near Tallahassee was shifted toward the northeast near the coast of Georgia. Rainfall over the Oklahoma region was also improved after assimilating SSM/I data (LGS and LGMS), in particular for the experiment that assimilated all observations (LGMS). The simulated rainfall near Tallahassee was produced with LGS, though underestimated. Similar to LGM and LGB, the rainfall from LGMS was shifted toward the northeast.

Using 3-hourly outputs from the LM experiment, a backward trajectory for 10 points from the 27-h integration back to the initial time (i.e., from 2100 UTC 2 June back to 1800 UTC 1 June; Fig. 9) was calculated to determine the origin of the moisture contributing to those rainfall regions. Compared to LN, in addition to the improvement of the convergence zone over the border of Oklahoma and Texas (Fig. 7d), the precipitation over the Oklahoma region was improved because a source air mass that was traced back to eastern and south-eastern Texas was moistened after the assimilation of MODIS TPW (LM), as shown in Fig. 10a. Furthermore, the removal of the false alarm at northern Louisiana and southern Mississippi (i.e., LN in Fig. 8b) was partially due to a reduction in moisture at the origins of the backward trajectories in southern Mississippi and western Alabama (Figs. 9 and 10a). Results from the thunderstorm simulations over the central and southern US indicate that the simulated winds and rainfall for this case study can be slightly improved after the assimilation of MODIS data.

Figure 10b shows the difference of TPW between LGS and LG (LGS – LG). Note that SSM/I data, which were available over ocean only, were assimilated at an earlier time in the data cycling period (Table 3), and therefore had a chance to propagate over the land. The increments after the assimilation of MODIS TPW and the assimilation of SSM/I retrievals in Fig. 10 present some similarities over the land. However, the difference over the ocean became more pronounced for this case. We suspect that retrieved SSM/I data, whose information was propagated over land during the data cycling period, had better quality, while MODIS nIR TPW data possibly had poorer quality over the ocean and underestimated TPW. More studies on the improvement of MODIS nIR TPW and the error characteristics of these data over the ocean through comparisons with other reliable observations are needed.

The difference between results after the use of MODIS TPW data with (i.e., LGM) and without (i.e., LGB) bias correction was not significant. The moisture increments for LGM and LGB (i.e., LGM – LN versus LGB – LN) at 1800 UTC 1 June 2004 were very similar, but LGM was slightly moister over high water vapor content regions (figure not shown). In this case study, although MODIS TPW data in the moist atmosphere were overestimated (i.e., larger innovation) in LGM, the use of a larger observational error (i.e., 4 mm) reduced the weight given to these data in data assimilation when compared to the assimilation with bias correction in LGB. The smaller weighting compensated for the effect of larger innovation values and, therefore, suppressed the difference between LGM and LGB. Further systematic study of the influence of the bias correction on severe weather simulations/forecasts is required.

4.2 Hurricane Isidore simulations

a. O1 experiments

The first assimilation test carried out for Hurricane Isidore (O1) began with the 3DVAR analyses at 1800 UTC 17 September and ran to 1800 UTC 20 September 2002. Figure 11 shows 3-day observed (i.e., from the best track positions) and simulated sea level pressure (SLP) at the storm's center and the maximum low-level wind speed. The observed storm slowly intensified over the first day as it skirted Jamaica. After that, Isidore quickly increased its intensity, with a SLP of 967 hPa and maximum low-level wind of 45 ms^{-1} at 0600 UTC 20 September, before it approached Cuba, at which time the storm started weakening. At the end of the third day (1800 UTC 20 September), the SLP at the storm's center was 965 hPa and the maximum low-level wind was 37.5 ms^{-1}. Compared with observations, all simulated storm intensities were too weak, except at the very end of the simulation for low-level wind from O1GS. For O1N, which did not assimilate any observations during the cycling period, the SLP was 36 hPa higher and the maximum low-level wind was 23 ms^{-1} weaker than observed after a 72-h integration. The assimilation of any set of observations was able to increase the simulated storm intensity except when only MODIS data was assimilated (i.e., O1M in Fig. 11).

It is interesting to see that the discrepancy in moisture between O1M and O1GM after the data cycling (i.e., 1800 UTC 17 September, 2000) was very minor (Figs. 12a versus 12b), but the simulated storm intensity from O1GM was much better than that from O1M (Fig. 11). For O1M, in addition to a slightly weaker simulated storm during the early integration period, the simulated track prevented the storm's development. The simulated storm deflected to the northeast of the observed track later in the simulation period and passed over Cuba. This inhibited the intensification of the storm due to the increase in surface friction and the decrease in the latent heat flux from the surface. This also occurred for the simulated track for O1N (Fig. 13a). The (additional) use of GTS data (e.g., O1GM) produced a northerly wind increment in the central region of domain 2 (i.e., Figs. 12a versus 12b in 500 hPa wind increments) and, in consequence, partially corrected the simulated storm track to a much better direction (line with the letter G in Fig. 13b), allowing the storm to develop more strongly. The error was significantly reduced during the last one and half days (gray line with filled triangles in Fig. 14a) but the simulated storm still moved too slowly. Compared with O1N, the SLP at the storm center deepened by 10 hPa and the maximum low-level wind strengthened by 13 ms^{-1} after a 72-h integration (Fig. 11). With the addition of assimilating original MODIS data (i.e., O1GM), the simulated storm intensity was greatly enhanced after the correction of the simulated track.

The pattern of the moisture increment from O1GB, which assimilated GTS data and bias-corrected MODIS TPW, was quite similar to that of O1GM, but the magnitudes were slightly different (Fig. 12c). Simulated storm intensities from O1GB and O1GM were close during the first two days (Fig. 11). The intensity from O1GB was slightly weaker during the third day. The use of SSM/I data produced a low-level divergence increment with a slightly cyclonic circulation around the simulated storm (Fig. 12d) and, unfortunately, increased the error of the initial storm position (Fig. 14a). The moisture increments due to the assimilation of MODIS TPW and the assimilation of SSM/I TPW were quite different over the ocean (Figs. 12a versus 12d). Nevertheless, the simulated storm intensity from O1GS was comparable to that of O1GM, except for the very last 12 hours (Fig. 11). The simulated SLP at the storm center deepened to 968.7 hPa and the simulated maximum low-level wind reached 45.5 ms^{-1} at the end of the O1GS simulation. The direction of the simulated storm motion was reasonable but the propagating speed was too slow. Simulated results after the additional use of MODIS TPW (i.e., O1GMS) were comparable to those from O1GS, but the simulated SLP and track were slightly worse for the last day. Although the error of the simulated track from O1GMS was relatively large compared with most of the other experiments (Figs. 13b and 14a), unlike O1N and O1M, the simulated storm was able to intensify since it stayed over the ocean during the simulation period. It is worth mentioning that a larger moisture increment around the storm area from O1GS implies that the influence of SSM/I data on the simulated storm could possibly be earlier than that of

MODIS TPW due to a large data void area around the storm for MODIS TPW (i.e., cloudiness). Though this result is not clearly shown in the O1 experiments (Fig. 11), this becomes more evident in the O2 experiments, which are discussed in next section.

b. O2 experiments

The second set of assimilation tests carried out for Hurricane Isidore (O2) began with the 3DVAR analyses at 1800 UTC 18 September and ran to 1800 UTC 21 September 2002, which is shifted one day later than the O1 experiments. Some conclusions drawn from the data assimilation analysis from the O1 experiments were also reached with the O2 tests. A northerly wind anomaly over the central region of domain 2 was obtained after the use of GTS data (Fig. 15a). O2GM (Fig. 15a) and O2M produced similar moisture increments, as expected. The bias correction of MODIS TPW in O2GB once again did not make a significant difference in analysis compared to O2GM. As mentioned before, due to a larger data void area around the storm for MODIS TPW, the assimilation of SSM/I data provided a much more extensive area around the storm with a large moisture increment (Figs. 15a versus 15b). However, unlike O1GS, the assimilation of SSM/I data resulted in a saddle pattern of low-level wind increments (Fig. 15b), and the error of the initial storm position was reduced after the data cycling (Fig. 14b).

Figure 16 shows the observed and 3-day simulated intensities for Isidore from the O2 experiments. Observed Isidore moved over the Caribbean Sea on the southwestern side of Cuba and intensified over 36 h. After that, the SLP stayed roughly constant and the maximum low-level wind weakened when the storm approached and then made landfall at the western edge of Cuba. Isidore regained strength after moving over the open ocean again. At 1800 UTC 21 September, i.e., at 72 h, Isidore deepened to a SLP of 946 hPa and reached a maximum low-level wind of 55 ms^{-1}. In contrast to the O1 experiments, all simulated storm intensities were stronger than those observed after 30-h integrations and beyond, except that of O2GS from 36 h to 42 h. At the end of the integrations, most of the simulated maximum low-level winds were close to the observed (Fig. 16b).

The storm intensities from O2N and O2G were very similar. Although both intensities were too strong, their trends were very close to the observed. Both simulated storm tracks passed over Isla de la Juventud, the small island to the south of western Cuba, and then turned left earlier than observed, skirting the southern coast of western Cuba (Fig. 17). The left turn had a similar weakening impact on the storm intensity as the effect of crossing land on the observed storm track. The simulated storm from O2N moved north-westward with the track offset to the northeast relative to the observed. This shift was corrected when GTS data was assimilated (i.e., O2G) due to the northerly wind increment in the 3DVAR analysis (Fig. 15b)..

The results from O2M, O2GM, and O2GB show that MODIS TPW had almost no influence on the storm intensity during the first one and a half day integration period. MODIS data started influencing the simulation of Isidore after 36 h. The assimilation of MODIS TPW (i.e., O2M) clearly improved the simulated intensity after 0600 UTC 20 September 2002 (i.e., after 36 h), and its trend was 6.4 hPa closer to observed than the control run O2N.

The simulated storms from O2GM and O2GB were stronger than those from O2G and O2M, which were already stronger than the observed. The former two experiments displayed no lull in the storm intensities (Fig. 16). This is because the simulated track from O2GB was shifted too far to the west and that from O2GM moved too slowly to be affected by passing over western Cuba (Fig. 17a). The discrepancies between the simulated storm intensities from O2GM and O2GB were indistinguishable (Fig. 16).

The assimilation of SSM/I data (e.g., O2GS), which were available over the cloudy areas over the ocean, influenced the simulated storms after an 18-h integration which was earlier than the effects from MODIS data (e.g., O2GM). This can be seen in the greater extent of the region with a large negative TPW increment around the storm, as mentioned earlier (Figs. 15a versus 15b). The primary reason for this was because MODIS data were void around the storm. The simulated storm from O2GS moved across western Cuba similar to the observed track, though a little further northeast, and its simulated intensity was better than those from the other O2 experiments (Fig. 16). The simulated SLP at the storm center was only 940.5 hPa, which was 8.5 hPa better than that from O2N. O2GMS also greatly improved the simulated storm intensity. The error in the simulated track was close to a constant over the whole simulation period causing its track to outperform others on the third day (Fig. 17b). In general, the O2 experiments better simulated tracks (Fig. 13 versus Fig. 17), and had significantly lower errors than the O1 experiments (Fig. 14a versus 14b), which started model integrations one day earlier.

5. Summary

Comparisons of MODIS TPW and GPS TPW over the continental US showed that the root mean square (RMS) differences between GPS and the two MODIS data products were about 5.2 and 3.3 mm for IR and nIR TPW, respectively. This implies that nIR retrievals are more precise than the IR retrievals. Results also showed that MODIS IR TPW data were overestimated in a dry atmosphere but underestimated in a moist atmosphere. In contrast, the nIR values were slightly underestimated in a dry atmosphere but overestimated in a moist atmosphere. After applying a bias correction, the RMS difference between MODIS nIR TPW and GPS TPW was reduced to 2 mm over the land. The trends in the differences between MODIS TPW and radiosonde TPW over the US and Australia were similar to those from GPS TPW, but the differences were larger. This could be because of the potential dry bias associated with radiosonde measurements reported in previous studies (Wang et al. 2002; Miloshevich et al. 2006). The comparison results suggest that the bias of MODIS TPW over the ocean (i.e., results from Willis Island) could be very different from that over land and merits further study. For this reason, the bias correction was applied only to MODIS nIR TPW pixels over land when assimilating the data.

The assimilation of MODIS nIR TPW data, along with conventional GTS data and SSM/I retrievals, into WRF model simulations was demonstrated for a severe thunderstorm case over the central to southern US in early June 2004 and for Hurricane Isidore over the ocean in September 2002. The results of the thunderstorm case over land show that the assimilation of MODIS nIR data slightly improved simulated rainfall over the region of interest in southern Oklahoma. This was because the low level convergence in that area was better simulated and because the moisture at the source, which was traced back to south-eastern Texas, was increased after the use of MODIS nIR TPW data. Interestingly, the impact of SSM/I retrievals on simulated wind and rainfall for the thunderstorm case study was similar to that of MODIS nIR TPW. Although SSM/I data were available only over the ocean, their influence was propagated over land after those data were assimilated. The influence of conventional GTS data on this particular case study was negligible, possibly because the quality of the reanalysis data over land was relatively good compared to over the ocean; in addition, only limited data were used (i.e., GTS data were assimilated only at the times when MODIS data were available).

Simulated intensities from the Isidore O1 experiments, which started at 1800 UTC 17 September 2002, were all too weak, especially when there was a large error in the simulated tracks. However, MODIS nIR TPW with the additional use of conventional GTS data (i.e., O1GM) greatly improved the simulated storm intensity. The improvement was partially explained by the northerly wind increments produced when using the GTS data that effectively corrected the simulated storm direction. In contrast, simulated intensities from the Isidore O2 experiments, which started at 1800 UTC 18 September 2002, were too strong for the last one and a half days, even though the simulated storm track was smaller. The use of MODIS nIR data alone (i.e., O2M) was able to improve the simulated storm intensity after a 36-h integration period. However the results were not conclusive because the combined GTS and MODIS nIR assimilation did not improve intensity. Although simulated results from the O1 experiment were quite different from the O2 experiments, some conclusions were similar: in general, GTS data had a positive impact on the simulated track, in particular the storm direction; the accuracy of the simulated storm intensity greatly depended on the simulated track (e.g., whether it reached landfall or not); the assimilation of MODIS nIR TPW improved the simulated intensity when the simulated track was reasonably well reproduced; and the simulated storm intensity with the use of SSM/I data was comparable to or slightly better than when using the MODIS nIR data. Note that the influence of MODIS data on the storm simulation can be delayed since no full column water vapor data over cloudy regions are available, while SSM/I data, which are available over cloudy areas, can influence the storm simulation earlier. This was clearly shown in the O2 experiments.

The difference in the moisture increments after assimilating MODIS nIR data with and without bias correction was relatively minor when compared with the differences between assimilating MODIS and the assimilation of other types of observations (i.e., SSM/I or GTS). This is perhaps because any overestimation of the MODIS nIR TPW data was compensated by the use of a larger observational error (i.e., less weighting) when compared with the use of bias-corrected data. Further systematic evaluation of the effect of the bias correction as well as investigation of the bias over ocean is needed. Nevertheless, this preliminary work demonstrates that MODIS data can have a positive impact relative to other types of data and have the potential to improve weather simulations and forecasts. More case studies are required in order to further substantiate these conclusions.

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